Blast vibration and impact sound control, measurement and documentation during two large-scale tunnelling projects

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Abstract
The paper presents the vibration and sound emission measurement campaigns carried out in 2007 in preparation for the Ceneri-Basistunnel construction. We also present the vibration measurement campaign conducted during the construction of the Zimmerberg-Basistunnel. Both tunnels form an integral part of the Swiss Federal Railway Company Neue Eisenbahn Alpentransversale project (NEAT). This strategic project comprised the construction of several new tunnels. Its aim is the improvement of the existing infrastructure. The improved infrastructure will be able to accommodate a larger volume of railway traffic that is also crossing the Alps at higher speeds. The construction of the Ceneri-Basistunnel commenced in 2006. Both the Zimmerberg-Basistunnel and the Ceneri-Basistunnel are located underneath densely populated areas. Therefore, noise and vibration emissions have to be kept to a minimum and must not exceed applicable codes of practice. In order to identify the most appropriate blasting strategy for the yet to be constructed Ceneri-Basistunnel, blasting trials were conducted. The paper presents the findings of these trials and identifies ways to reduce both noise and vibration emissions from blasting. The construction of the first phase of the Zimmerberg-Basistunnel took place between 1999 and 2003. While the first phase is already in operation, the construction of the second phase has been postponed (commencement originally due in 2007). The Zimmerberg-Basistunnel connects the outskirts of Zürich with the city centre. As the tunnel site was not located close to the surface near populated grounds, no special measures were needed to reduce the noise emissions from blasting. However during the construction of the tunnel, the vibration emissions from blasting were monitored on more than 50 locations on the surface. The paper presents the analysis of some of the data. An emphasis is placed on the appropriate synopsis and presentation of data for documentation purposes.

Introduction
Over one-hundred kilometres of tunnel are constructed for the Swiss federal railway authorities' Swiss Neue Eisenbahn Alpentransversale (new railway Alp crossing project). The Ceneri-Basistunnel with a length of 15,4 km and the Zimmerberg Basistunnel with a length of 11,0 km make up only two out of several NEAT projects. As a the majority of the tunnels in Switzerland are built in densely populated areas, it is vital to control noise and vibration emissions from the construction works (blasting), and to find ways to minimize these emissions. Furthermore, it is necessary to measure, record and document construction emissions in order to defend against unjustified claims from third parties. This paper describes the trials that were conducted to optimise blast technology in terms of emission reduction for the Ceneri-Basistunnel. It further presents the data from a large blast vibration monitoring regime that was conducted during the construction of first phase of the Zimmerberg-Basistunnel.
Blast trials in preparation of the Ceneri-Basistunnel construction

The client wanted to determine the influence of different forms of borehole isolation on blast vibration and on noise emissions from both impact sound and airborne sound emissions. The following assumptions were to be verified:

1. Noise emissions are reduced using mineral wool rods. The optimum rod length and density was to be determined experimentally.
2. Airborne sound emissions can be reduced from boundary blasts, when the fuse is kept inside the borehole and insulated as opposed to having the fuse coming out of the hole and penetrating the isolation.

The trials were conducted in two different geological grounds at the experimental tunnel Hagerbach, in order to reflect the different geological conditions that would be encountered during the construction of the Ceneri-Basistunnel.

Blast trials in limestone/gravel ground

The picture above (left) shows the preparation of blast site for the first blast trial in the experimental tunnel at Hagerbach. Shown is the installation of the detonators and mounting of the isolation. A sketch of the tunnel and its surrounding is shown in the drawing at the right hand side. The locations of the various measurement sites relative to the blast site for vibration, airborne sound and impact sound measurements are indicated in the sketch. All but one measurement site were located inside the tunnel. A remote vibration measurement site was installed at a farmers house (Bauernhaus) located at a distance of 270 meters away from the blast site.

Altogether, four blast trials were conducted at the first site. The diagram to the left shows the blast sequence of the first trial. At LP0 no isolation was used, at LP 20, which was detonated with a delay of 2 seconds, 0,25 meters of mineral wool with a density of 65 kg/m³ were used. LP40 and LP60 were detonated with 2 seconds delay each and the density of mineral wool was 100 kg/m³ and 160 kg/m³ respectively.

The second trial site was located about 1,5m underneath the first trial site. The blast trial was conducted in the same manner, except that the isolation had a length of 0,50 meter instead of 0,25 meter. For the third blast trial polyurethane foam was used instead of mineral wool, and the forth blast trial was carried out without any isolation.
The vibration emissions were reduced with increasing distance from the blast location. The reduction factor was about 50% for a distance from 20 meters \(^1\) to 35 meters and to about 3% from 20 meters to 270 meters. In principle, there was no difference regarding the vibration emissions with regard to the used (or not used) isolation of the borehole. In other words, isolation did not reduce the vibration or sound emissions.

The results of the airborne sound and impact sound emission measurements are similarly compared to the findings of the vibration measurement. The microphone in airborne sound isolated borehole at a distance of 20 meters (picture to the right) gave about 6dB lower readings compared to the microphone located at a distance of 100 meters, but without any isolation (A reduction of 6dB is equal to a noise reduction by 50%).

In the diagram below shows the results of vibration and impact sound measurements at a distance of 20 meters from the blast site. This is the point where differences in emissions due to the effects of isolation should be the most obvious. However, it was not possible to distinguish between the blasts of the different trials as the results were similar (see diagram below). It was thus not possible to verify the first of the aforementioned assumptions. Therefore, no further trials were carried out.

**Blast trials in lithographic stone ground**

Boundary blasts are used to prepare the circumference for the main blast. The surrounding rock is thereby protected against damage by the greater impact energy from the main blast. The second assumption was that airborne sound emissions could be reduced significantly by using isolated boundary blasts in combination with a limited fuse length. The length was limited to the length of the borehole. In general, boundary blasts carry less explosive material compared to the main blast. Therefore, the fuse is laid openly and the blast holes are not isolated.

\(^1\) Due to technical reasons it is not possible to carry out measurements directly at the blast site. The equipment would have been destroyed. The closest possible distance was 20 meters away from the measurement site.
It was believed that the noise emissions from the boundary blasts could therefore even be louder than those from the main blast. The trials were conducted to verify this assumption. As the second trial site was already prepared for the discontinued trials, the tests were continued at the lithographic stone ground at the Hagerbach site. The blast location and the measurement points are shown on the previous page. The drawing below at the right shows the first setup of a total of three trial setups.

The first set of boundary blasts was carried out at intervals from 0 to 500 milli-seconds. The boreholes are located at the top and labelled by numbers '0' to '5'. The second set was carried out at 4 second intervals (circles labelled with '40') and the third cycle was located at the left hand side and carried out at 6 second intervals (circles labelled with '60'). Only the boreholes of the last cycle were isolated using mineral wool. The density of the wool was 100 kg/m³. First impressions of the test personal were that the third set of blast had been quieter compared to the previous two sets of blasts.

The second set of trial boundary blasts were conduced in a similar fashion as the first trial, except that the second set of blasts was also isolated with mineral wool. The last of the three trials was conducted using mineral wool as isolation for the last set of boundary blasts and polyurethane foam for the second set of blasts. The result of the measurements are shown below for the first and second set of blasts for the airborne sound emissions (Luftschall) and for the impact sound emissions.
The results of the vibration measurements show a beneficial effect when dense isolation material such as mineral wool (> 100 kg/m³) or polyurethane foam is used for the borehole isolation. Also, it is possible to clearly identify a reduction in both impact sound and airborne sound by about 50% (by about 4 to 6dB), when the boundary blasts are isolated and when the fuse is kept inside the borehole behind the isolation. The benefits of borehole isolation can be used when the tunnel portals are build nearby populated areas.

Other findings such as the comparison of impact sound from drilling of the blast holes shown that the impact sound emissions in dry lithographic stone were significantly higher at distances of 20 meters from the site (57 dB) compared to the limestone/gravel ground (45 dB at 20m). Also the frequency of the impact sound was higher for the lithographic stone, where the impact sound was transmitted at frequencies of 100 to 2000 Hz. Due to the good transmission properties of lithographic stone, it is possible that impact sound is recognizable at distances of about 100 meters from the site. This could cause problems with residences, especially during night times and will be considered during the construction phase of the tunnel.

Whereas the trials are beneficial to help identifying the optimal way to carry out tunnelling blasts prior to construction, it is still necessary to monitor vibration and, where applicable, sound emissions when tunnels are constructed in densely populated areas. Monitoring is the only way to control, eliminate where possible, and to document any emissions.

**Blast vibration measurement during the construction of the Zimmerberg-Basistunnel**

The Zimmerberg-Basistunnel construction project comprises 2 phases. The first phase of Zimmerberg-Basistunnel was constructed from 1999 until 2003. The second phase has not yet commenced. Blasting works were carried out from 1999 until 2001. The section of the tunnel affected by the works had a length of about 1,5 km and is shown in the drawing below. The vibrations emissions were monitored for a period of 2 years from about 50 locations on the surface. The results were evaluated according to Swiss Standard SN 640312a (1992).
For each of the measurement locations approximately 1000 blasts were recorded and documented as shown to the left. The diagram shows the vibration speed as the vector sum of the x-, y- and z-components, the three components and the respective dominant frequency. The diagram was plotted immediately. The diagrams were then compared to applicable threshold values. The emissions had to stay within the limits of codified values and, if necessary, the monitoring regime was used to amend the blasting works so that emissions were reduced.

In total about 30000 individual blast records were made at the different locations. All of them were further analysed to obtain the damping formula for different locations and to assess the vibration emissions for locations where no sensor had been installed during blasting works (see diagram at the bottom of the page). In general, vibration emissions reduced to a fraction of their value at distances greater 200 meters away from the blast site and could be ignored for further analysis (see middle diagram).

Overall, the vibration emissions were deemed within the acceptable boundaries and a final report was issued in a concise form to summarise the 30000 or so individual records within 10 to 15 page report.
Documentation, evidence preservation and data extraction

The summary report, which was issued in 2002 was intended for the use of experienced engineers. It was obvious to a professional engineer experienced with vibration measurement and blast technology that all vibrations had been well within the limits of the applicable standards (top down approach). However, as the raw data had been presented (on purpose) sparsely in order to present a concise report, the report did not show in detail the vibration emissions for each of the populated sites (residential houses) on the surface.

In due course, a detailed vibration analysis for one of the sites became necessary in order to show that the emissions did not exceed the applicable boundaries (bottom up approach). The process for the vibration analysis according to SN 640312a (1992) is shown in detail in the diagram below:

As it was not economically viable to place a sensor at each residential property located above tunnel, the distance of each of the blast campaigns to the site in question had to be shown in order to identify the relevant blast campaigns for the site. All blasts within a 200 meter radius around the site were considered “relevant” in terms of potential vibration emissions (see left for time/location diagram for one of nine blast campaigns).
From twelve blasting campaigns that were conducted during the construction works, only five campaigns did stretch into the 200 meter perimeter around the scrutinised location. Furthermore, a sensor had been in place at the site in question for most of the time. However, for a period of about 2 weeks no sensor was located at the site directly, while blasts were already conducted within the 200m radius.

The diagram below shows the distance to the sites where the maximum blast vibrations were recorded and the respective blast vibration speed (gray lines) and the distance to the site, that was analysed in detail (black lines). It became obvious that the distance of the scrutinized site to the blasts was significantly greater than the distance of other sites where the maximum blasts were recorded. Furthermore, a sensor had been in place at the scrutinized site except for the two initial weeks. It could be demonstrated, however, that the scrutinized site was always further away from the blast sites than the sites where the maximum recordings were taken.

Furthermore, using the regression analysis for the damping function, the blast vibrations at the site were calculated for the two weeks where no sensor had been in place. The calculated data was then verified with data gained from actual blast records and a good match was achieved. Then a detailed analysis according to SN 640 312a was carried out. It could be demonstrated in layman terms what had been clear to an experienced engineer from the beginning: that there were no vibration emissions whatsoever at the site in the sense of the standard.

This very detailed and costly analysis had become necessary only because of the misunderstandings and misinterpretations which can be read into any concise engineering report, where information has to be omitted for the sake of clarity and conciseness. This is a dilemma as reports should summarise large amounts of data. No detail is needed, but a short summary of the engineering findings. On the other hand when claims have to be verified (or rendered void), it is difficult to defend ones position based on the summary report alone. It could become necessary to go into a level of detail that would otherwise be uneconomical. What would have happened if no monitoring system would have been installed at all? In this case, the chances of the builder owner to defend himself against claims would have been slim indeed.
Summary

It has been shown that it is possible to optimise blast technology in a way that noise emissions are reduced. The noise emissions from blasting can be reduced by 50% using the right fuse and blast hole isolation for boundary blasts. The optimisation of blasts will help to increase the acceptance of blasting works, especially in densely populated areas, and reduce complaints from residents. It has also been shown that monitoring campaigns are necessary to monitor vibration emissions where blasting works are conducted (e.g. tunnel construction). Monitoring campaigns form one of the cornerstones of emission control and documentation. When the builder-owner might have to defend against claims, re-visitation of data is possible in order to clear individual cases.

Bibliography

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